

Diboson polarisation measurements in ATLAS

Luka SELEM

On behalf of the ATLAS Collaboration

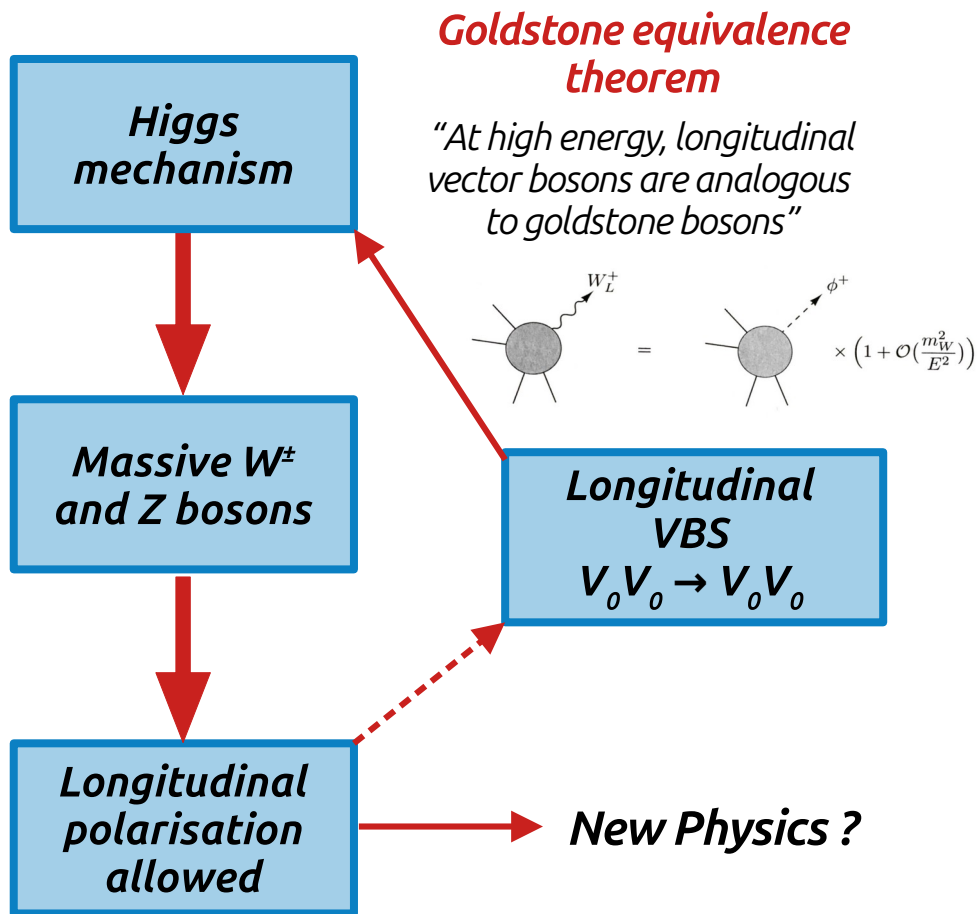
QCD@LHC

01/10/2026



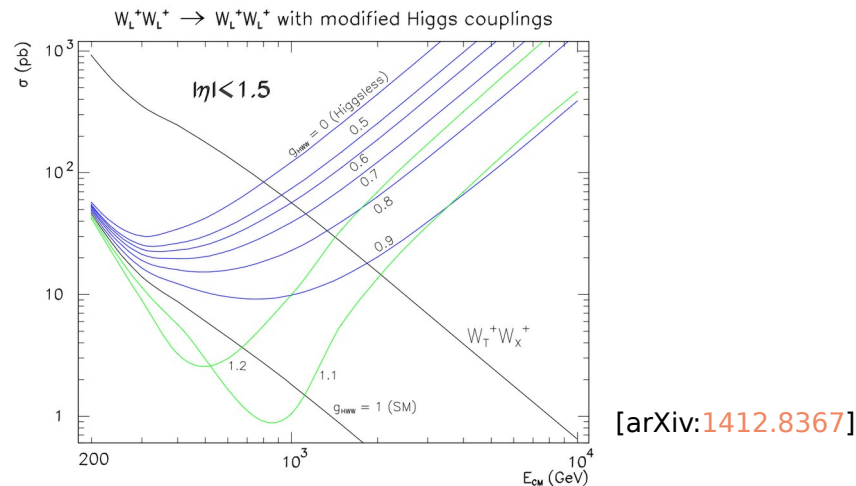
Université
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Motivation



Longitudinal VBS

→ Small fraction of the rare VBS events



First steps in that direction

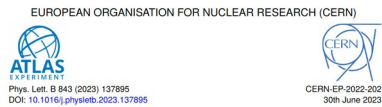
- **Inclusive** diboson **joint-polarisation**
- **Polarisation** in **VBS**

→ Opportunity to look for **deviations**

Previous results in ATLAS

November
2022

**Inclusive WZ
joint-polarisation**



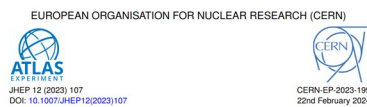
**Observation of gauge boson joint-polarisation states
in $W^\pm Z$ production from pp collisions at
 $\sqrt{s} = 13$ TeV with the ATLAS detector**

The ATLAS Collaboration

Measurements of joint-polarisation states of W and Z gauge bosons in $W^\pm Z$ production are presented. The data set used corresponds to an integrated luminosity of 139 fb^{-1} of proton-proton collisions at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector at the CERN Large Hadron Collider. The $W^\pm Z$ candidate events are reconstructed using leptonic decay modes of the gauge bosons into electrons and muons. The simultaneous pair-production of longitudinally polarised vector bosons is measured for the first time with a significance of 7.1 standard deviations. The measured joint helicity fractions integrated over the fiducial region are $f_{00} = 0.067 \pm 0.010$, $f_{0\pm} = 0.110 \pm 0.029$, $f_{\pm 0} = 0.179 \pm 0.021$ and $f_{\pm\pm} = 0.644 \pm 0.032$, in agreement with the next-to-leading-order Standard Model predictions. Individual helicity fractions of the W and Z bosons are also measured and found to be consistent with joint helicity fractions within the expected amounts of correlation. Both the joint and individual helicity fractions are also measured separately in $W^\pm Z$ and $W^\pm Z$ events. Inclusive and differential cross sections for several kinematic observables sensitive to polarisation are presented.

October
2023

**Inclusive ZZ
joint-polarisation**



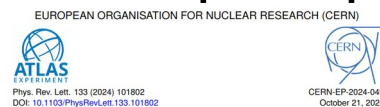
**Evidence of pair production of longitudinally
polarised vector bosons and study of CP properties
in $ZZ \rightarrow 4\ell$ events with the ATLAS detector at
 $\sqrt{s} = 13$ TeV**

The ATLAS Collaboration

A study of the polarisation and CP properties in ZZ production is presented. The used data set corresponds to an integrated luminosity of 140 fb^{-1} of proton-proton collisions at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector at the Large Hadron Collider. The ZZ candidate events are reconstructed using two same-flavour opposite-charge electron or muon pairs. The production of two longitudinally polarised Z bosons is measured with a significance of 4.3 standard deviations, and its cross-section is measured in a fiducial phase space to be $2.45 \pm 0.60 \text{ fb}$, consistent with the next-to-leading-order Standard Model prediction. The inclusive differential cross-section as a function of a CP-sensitive angular observable is also measured. The results are used to constrain anomalous CP-odd neutral triple gauge couplings.

February
2024

**Inclusive WZ
joint-polarisation in
00-enriched phase space**



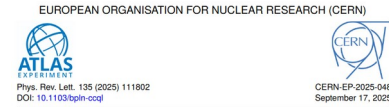
**Studies of the energy dependence of diboson
polarization fractions and the Radiation Amplitude
Zero effect in WZ production with the ATLAS
detector**

The ATLAS Collaboration

This Letter presents the first study of the energy-dependence of diboson polarization fractions in $WZ \rightarrow \ell\nu\ell^*\ell^*$ ($\ell, \ell^* = e, \mu$) production. The data set used corresponds to an integrated luminosity of 140 fb^{-1} of proton-proton collisions at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector. Two fiducial regions with an enhanced presence of events featuring two longitudinally-polarized bosons are defined. A non-zero fraction of events with two longitudinally-polarized bosons is measured with an observed significance of 5.2 standard deviations in the region with $100 < p_T^Z \leq 200 \text{ GeV}$ and 1.6 standard deviations in the region with $p_T^Z > 200 \text{ GeV}$, where p_T^Z is the transverse momentum of the Z boson. This Letter also reports the first study of the Radiation Amplitude Zero effect. Events with two transversely-polarized bosons are analyzed for the $\Delta\Gamma(\ell\nu Z)$ and $\Delta\Gamma(WZ)$ distributions defined respectively as the rapidity difference between the lepton from the W boson decay and the Z boson and the rapidity difference between the W boson and the Z boson. Significant suppression of events near zero is observed in both distributions. Unfolded $\Delta\Gamma(\ell\nu Z)$ and $\Delta\Gamma(WZ)$ distributions are also measured and compared to theoretical predictions.

March
2025

**Same-sign WW VBS
single polarisation**



**Evidence for longitudinally polarized W bosons in
the electroweak production of same-sign W boson
pairs in association with two jets in pp collisions at
 $\sqrt{s} = 13$ TeV with the ATLAS detector**

The ATLAS Collaboration

This Letter reports the first evidence of electroweak production of same-sign W boson pairs where at least one of the W bosons is longitudinally polarized and the most stringent constraint to date for the production of two longitudinally polarized same-sign W bosons. The data set used corresponds to an integrated luminosity of 140 fb^{-1} of proton-proton collisions at a centre-of-mass energy of 13 TeV, collected with the ATLAS detector during Run 2 of the Large Hadron Collider. The study is performed in final states including two same-sign leptons (electrons or muons), missing transverse momentum, and at least two jets with a large invariant mass and a large-rapidity difference. Two independent fits are performed targeting the production of same-sign W bosons with at least one, or two longitudinally polarized W bosons. The observed (expected) significance of the production with at least one longitudinally polarized W boson is 3.3 (4.0) standard deviations. An observed (expected) 95% confidence level upper limit of 0.45 (0.70) fb is reported on the fiducial production cross-section of two longitudinally polarized same-sign W bosons.

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Phys. Lett. B 843 (2023) 137895

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JHEP 12 (2023) 107

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Phys. Rev. Lett. 133 (2024) 101802

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Phys. Rev. Lett. 135 (2025) 111802

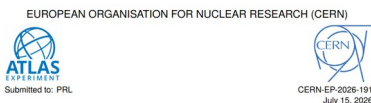
Only Run 2 results

NEW results (this talk)

July 2026



Inclusive ZZ
joint-polarisation
Observation of 00

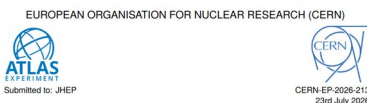


Observation of pair production of longitudinally polarised Z bosons in four-lepton final state with the ATLAS detector

The ATLAS Collaboration

The production of two longitudinally polarised Z bosons is measured using proton-proton collision data recorded by the ATLAS experiment at a center-of-mass energy $\sqrt{s} = 13.6$ TeV and with an integrated luminosity of 164 fb^{-1} . The ZZ candidate events are reconstructed using two same-flavor opposite-charge electron or muon pairs. The polarization fractions of the Z boson pair are measured inclusively in the fiducial phase space and also in two regions of the four-lepton invariant mass, and the results are consistent with the Standard Model predictions. After a statistical combination with a previous measurement at $\sqrt{s} = 13$ TeV, the first observation of the production of two simultaneously longitudinally polarised Z bosons is obtained, with observed and expected significances of 6.5 and 5.6 standard deviations, respectively.

WZ VBS
single polarisation
Evidence for Z0



Evidence for longitudinally polarised Z bosons in electroweak $W^\pm Z$ production in association with two jets from pp collisions at $\sqrt{s} = 13$ TeV and 13.6 TeV with the ATLAS detector

The ATLAS Collaboration

Measurements of polarisation states of W and Z gauge bosons in electroweak $W^\pm Z$ production in association with two jets ($WZjj$ -EW) in proton-proton collisions are presented. The data set used corresponds to integrated luminosities of 140 fb^{-1} and 164 fb^{-1} of proton-proton collisions at centre-of-mass energies of 13 TeV and 13.6 TeV, respectively, recorded by the ATLAS detector at the CERN Large Hadron Collider. The $W^\pm Z$ candidate events are reconstructed using leptonic decay modes of the gauge bosons into electrons and muons. The observed significance for the presence in data of $WZjj$ -EW events containing a longitudinally polarised Z boson is of 4.0 standard deviations. The measured fraction of such events, integrated over the fiducial region, is $f_{\text{pol}} = 0.32 \pm 0.09$, in agreement with the Standard Model prediction at next-to-leading-order in electroweak corrections. Upper limits at 95% confidence level of 0.19 and 0.12 are set on the fraction of events with a W boson longitudinally polarised and on the fraction of events with the two bosons longitudinally polarised, respectively. The integrated fiducial cross-section per lepton flavour of $WZjj$ -EW production at $\sqrt{s} = 13.6$ TeV is also measured to be $\sigma_{WZjj\text{-}EW\text{-}l^+l^-} = 0.374 \pm 0.077 \text{ (stat.)} \pm 0.053 \text{ (syst.)} \pm 0.009 \text{ (lumi.) fb}$, where l and $\bar{l}$ are either an electron or a muon. This measurement is in agreement with the Standard Model expectation.

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*First results
using Run 3
data !*

140 fb⁻¹ + 164 fb⁻¹

Signature	Run 2	Run 2 + partial Run 3
W[±]Z	Observation 00	
ZZ	Evidence 00	
VBS W[±]W[±]	Evidence W ₀	
VBS W[±]Z		

*Only
leptonic
decays
considered*

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ArXiv: 2607.12879

ArXiv: 2607.20246

What is polarisation really ?

Fundamentally quantum : spin density matrix

- Diagonal terms = “pure polarisations”
- Off-diagonal = interferences

$$\begin{aligned}
 f_{00} &= \rho_{0000} , \\
 f_{TT} &= \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++} , \\
 f_{0T} &= \rho_{00--} + \rho_{00++} , \\
 f_{T0} &= \rho_{--00} + \rho_{++00} .
 \end{aligned}$$

$$\text{Tr}(\rho) = 1$$

*Polarised Matrix
element*

$$\rho_{\lambda_W \lambda'_W \lambda_Z \lambda'_Z} \equiv \frac{1}{C} \times \sum_{\mu_q \mu_{\bar{q}}} F_{\lambda_W \lambda_Z}^{(\mu_q \mu_{\bar{q}})} F_{\lambda'_W \lambda'_Z}^{(\mu_q \mu_{\bar{q}})*}$$

Normalisation

$$C = \sum_{\mu_q \mu_{\bar{q}} \lambda_W \lambda_Z} \left| F_{\lambda_W \lambda_Z}^{(\mu_q \mu_{\bar{q}})} \right|^2$$

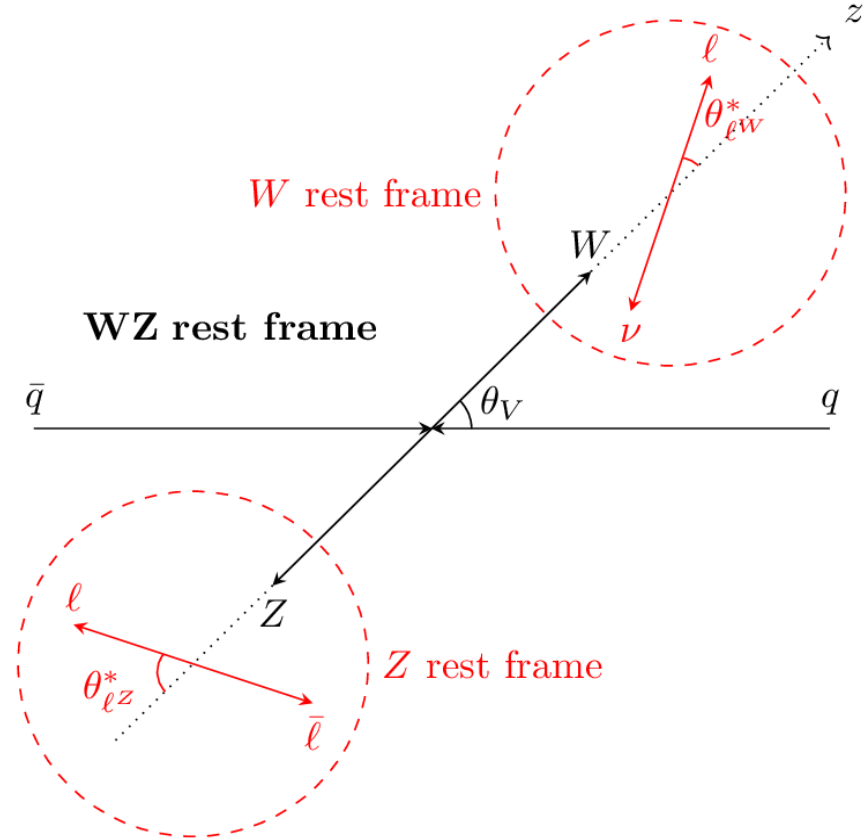
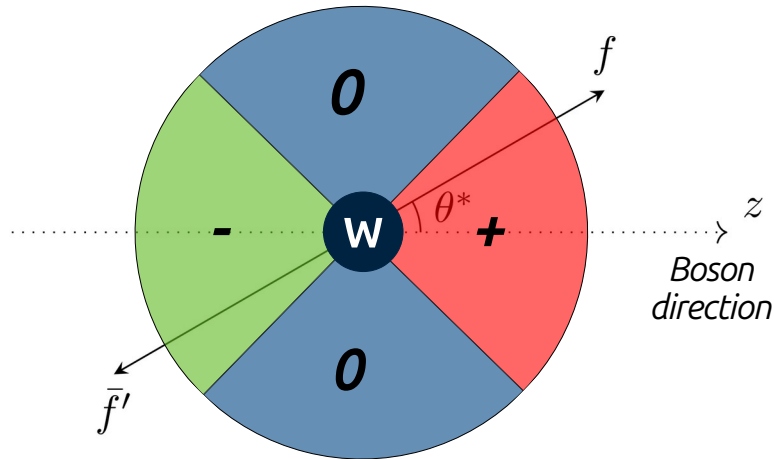
Averaging on quark polarisations

Frame choice

Polarisation → Angular variables

Frame dependence

- Natural choice is **diboson rest frame**
- **NOTE**: Different from the helicity frame



Ingredients for polarisation measurements

Method : Fit on data with polarisation templates

Discriminating variable :

- Extract **as many polarisations as possible** : Model independence !
- Low statistics → struggle to keep significance

Polarised templates

- Representative of **higher order corrections** ?
- **Modelling uncertainty**
- **Interference term** ? Non-resonant background ?

Polarisation in ZZ inclusive

ArXiv: 2607.12879

Signal region composition

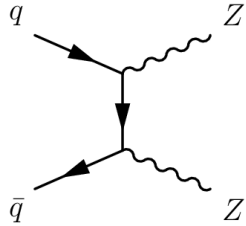
Very clean signature :

$$pp \rightarrow \ell \bar{\ell} \ell' \bar{\ell}'$$

Signal

qq→ZZ

~83% of SR events

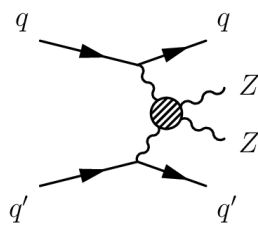


Sherpa 2.2.16
inclusive

Madgraph 0,1,2jet LO
polarised

qq→ZZjj (VBS)

~1% of SR events



Sherpa 2.2.14
inclusive

Madgraph LO
polarised

Σ

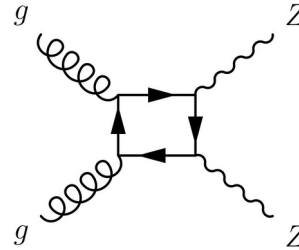


Inclusive – **LL: ~7%** of SR events
TL: ~22% of SR events
TT: ~54% of SR events

Interference :
~1.5% of SR events

gg→ZZ

~14% of SR events



Sherpa 2.2.12 inclusive

Others

<2% of SR events

- Fakes
- ttZ
- triboson

Challenge : low signal events yields

~3000 (Run2) + ~3000 (partial Run3) events

➔ ~400 $Z_L Z_L$ polarisation events

Discriminating variable

Templates obtained directly from generators

→ $Z_L Z_L$, $Z_L Z_T$, $Z_T Z_T$ ($T = \text{Left} + \text{Right}$, undiscernable Z bosons)

Full angular information

→ **BDT trained for LL against LT&TT**

BDT variables

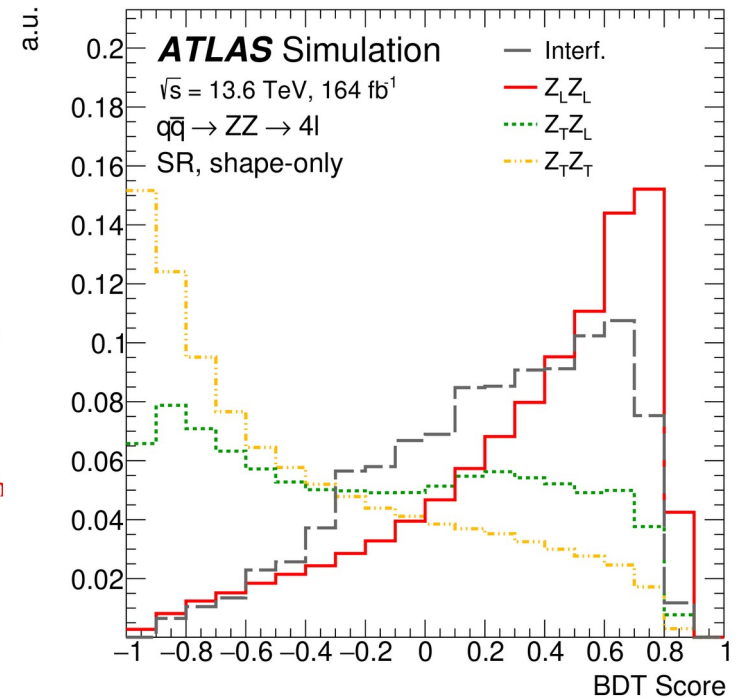
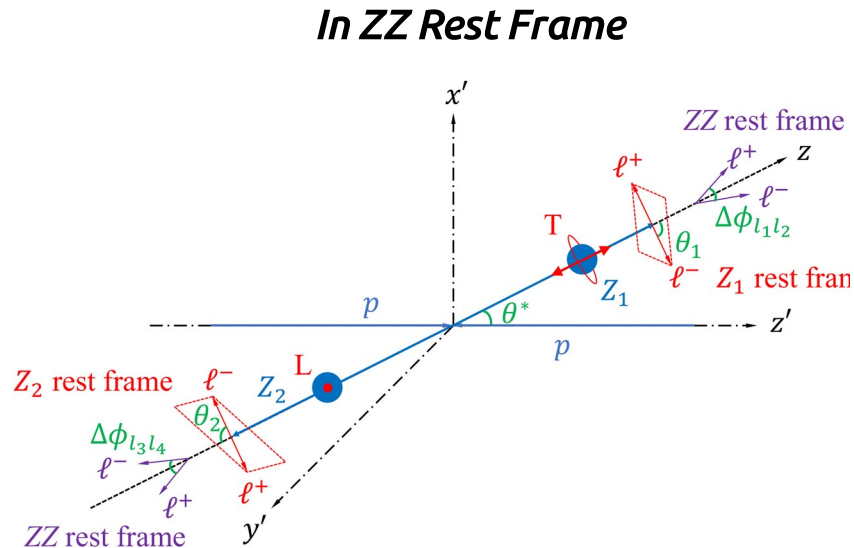
$$\cos\theta_1$$

$$\cos\theta_2$$

$$\cos\theta^*$$

$$\Delta\phi_{l_1 l_2}$$

$$\Delta\phi_{l_3 l_4}$$



Polarisation templates

Polarised generation with **MadGraph** : $qqZZ + qqZZjj$

Reweighting (for $qqZZ$)

- **1D** reweighting along $\cos\theta_1$ of each polarised template to **fixed order MoCaNLO polarised NLO QCD+EW**
- **Interference term Sherpa3** BDT distribution (Inclusive – Σ polarised)_{particle level} reweighted to detector level
- **2D** reweighting along $\cos\theta^*$ and $\Delta\phi_{l1l2}$ of (Σ polarised) to (Inclusive – Interference)

Modelling uncertainty

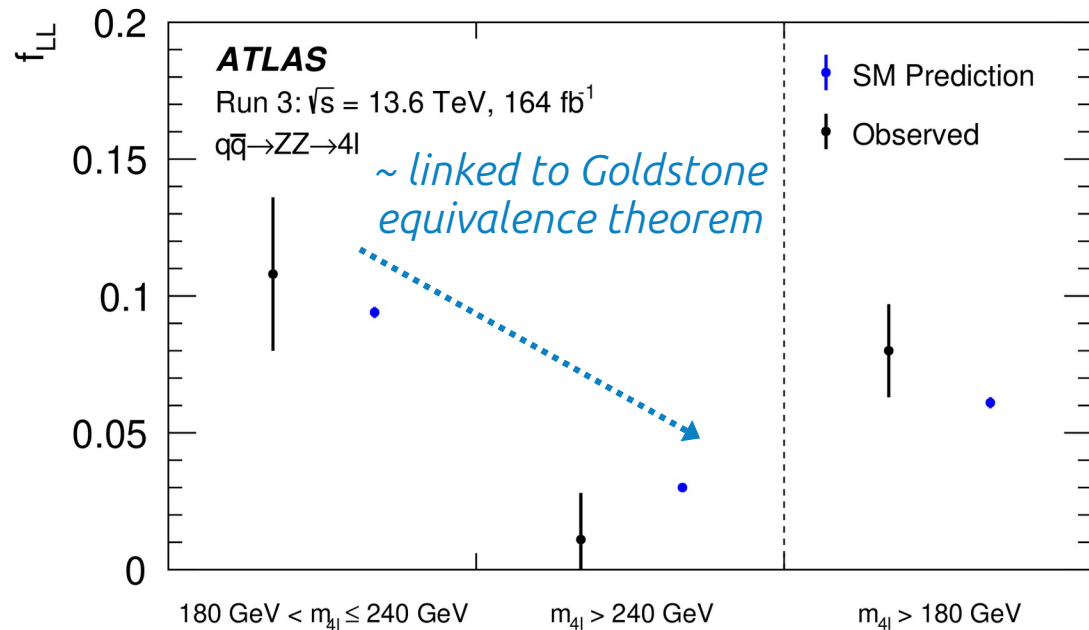
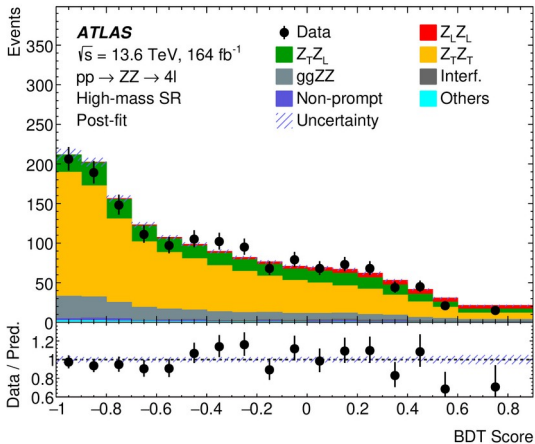
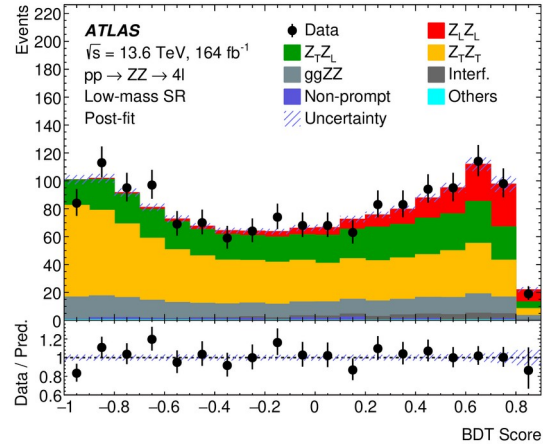
- Systematic from difference to prediction from **Sherpa3 NLO QCD polarised** at particle level
→ **Uncorrelated** between each polarisation template
- NLO EW and QCD uncertainties, PDF, ...

Run 3 results

Fit in 2 mass regions : $180 \text{ GeV} < M_{4l} < 240 \text{ GeV}$; $M_{4l} > 240 \text{ GeV}$

$$\rightarrow \mu_{LL} = 1.34 \pm 0.26(\text{stat.}) \pm 0.13(\text{syst.}) \quad 5.1\sigma \text{ obs.} \quad 4.1\sigma \text{ exp.}$$

Measure **LL fraction** in both mass regions :

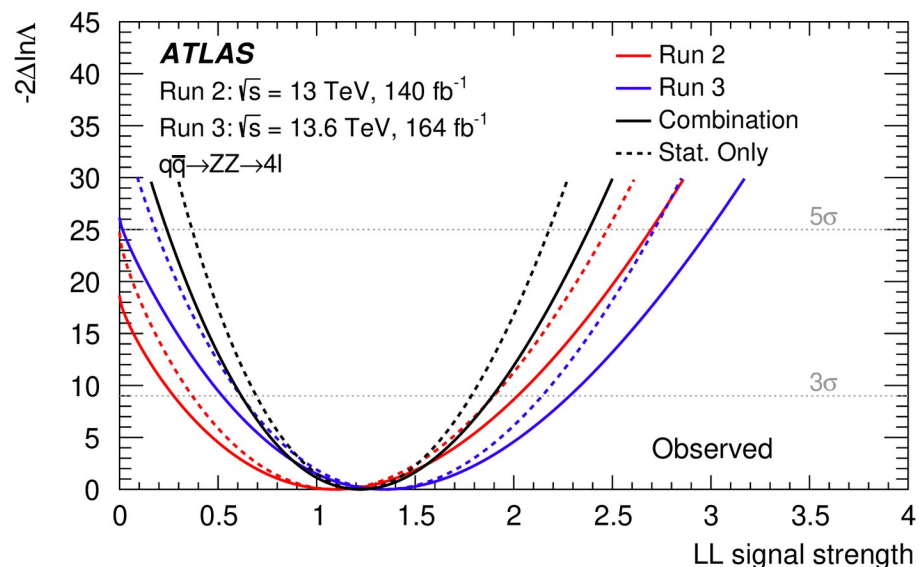


Combination with Run 2 : Observation

Combined statistical analysis with Run 2 data :

$$\rightarrow \mu_{\text{LL}} = 1.22 \pm 0.21 \quad 6.5\sigma \text{ obs.} \quad 5.6\sigma \text{ exp.}$$

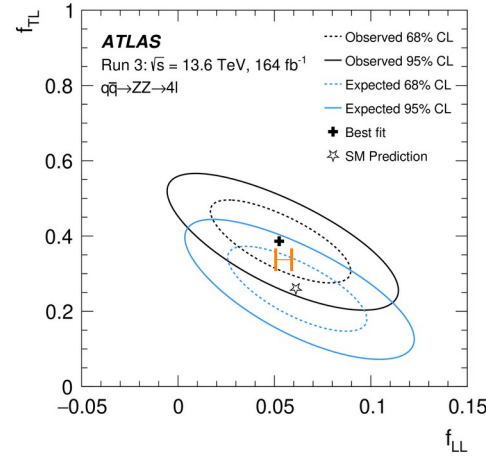
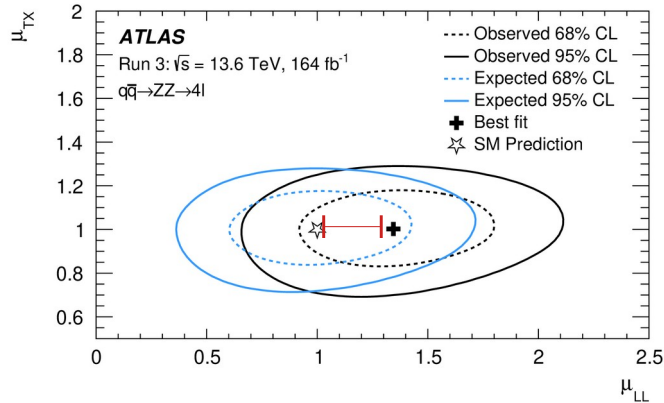
Main uncertainties : **statistical power** and **modelling**



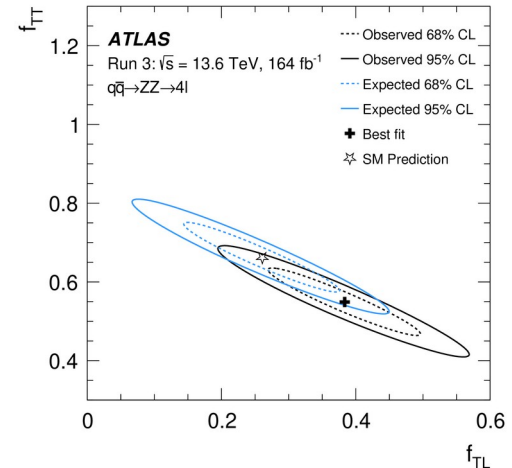
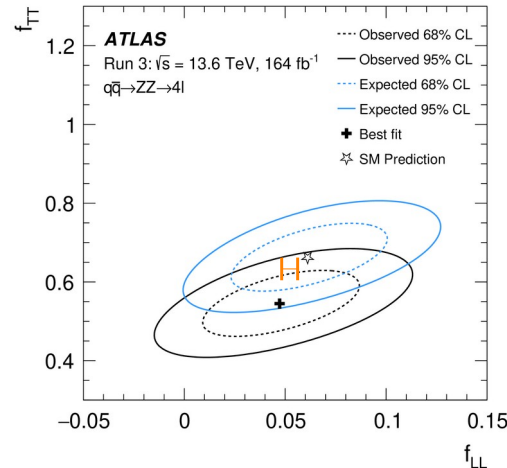
Contribution	Relative uncertainty [%]
Total	22
Data statistical uncertainty	19
Total systematic uncertainty	9.4
MC statistical uncertainty	2.3
Theoretical systematic uncertainties	
$q\bar{q} \rightarrow ZZ$ interference modeling	1.0
SHERPA 3 shape difference for $q\bar{q} \rightarrow ZZ$	2.2
QCD scale for $q\bar{q} \rightarrow ZZ$	0.5
PDF and α_s for $q\bar{q} \rightarrow ZZ$	3.2
Parton shower for $q\bar{q} \rightarrow ZZ$	1.7
NLO EW corrections for $q\bar{q} \rightarrow ZZ$	2.9
QCD scale for $gg \rightarrow ZZ$	3.9
PDF and α_s for $gg \rightarrow ZZ$	0.3
Experimental systematic uncertainties	
Luminosity	2.1
Muons	0.7
Electrons	6.0
Non-prompt background	0.4
Pileup modeling	0.5
Triboson and $t\bar{t}Z$ normalizations	0.1

Lesson 1 : The importance of more templates

From 2 templates (LL vs TX) to 3 templates (LL, TT, TL)



Closer to the SM expectation with **more templates** independently constrained



$\sim 1\sigma$ excess in μ_{LL} ?

Lesson 2 : Treatment of interferences

First polarisation analysis to explicitly treat the interference term

– Interference term scaled by the fractions values

➔ “Effective fractions” $\neq$ spin density matrix coefficient $f_{LL} + f_{TX} + \kappa\sqrt{f_{LL}f_{TX}} = 1$

$$\kappa = \frac{N_{\text{int}}^{\text{SM}}}{\sqrt{N_{LL}^{\text{SM}} N_{TX}^{\text{SM}}}}$$

– Interference term fixed

➔ More conservative, spin density matrix coefficient

	μ_{LL}		Significance (σ)	
	Observed	Expected	Observed	Expected
Scaled normalization for the interference term				
Run 3	1.34 ± 0.29	1.00 ± 0.27	5.1	4.1
Run 2	1.09 ± 0.29	1.00 ± 0.27	4.3	4.2
Combined	1.22 ± 0.21	1.00 ± 0.20	6.5	5.6
Fixed normalization for the interference term				
Run 3	1.35 ± 0.31	1.00 ± 0.30	4.5	3.6
Run 2	1.06 ± 0.32	1.00 ± 0.30	3.5	3.5
Combined	1.21 ± 0.23	1.00 ± 0.22	5.5	4.8

	Observed		Expected
	Scaled normalization for the interference term	Fixed normalization for the interference term	
f_{LL}	0.080 ± 0.017	0.080 ± 0.018	0.061 ± 0.002
$f_{LL}^{\text{low-}m_{4\ell}}$	0.108 ± 0.028	0.110 ± 0.030	0.094 ± 0.002
$f_{LL}^{\text{high-}m_{4\ell}}$	0.011 ± 0.017	0.009 ± 0.021	0.030 ± 0.001

Impact mostly on uncertainties

Polarisation in WZ VBS

ArXiv: [2607.20246](#)

Signal region composition

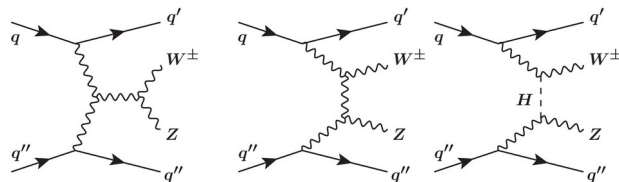
Signature = compromise

$$pp \rightarrow \ell\bar{\ell} \ell' \nu jj$$

Number of events vs Reconstruction (neutrino)

Signal : WZjj-EW

~13% of SR events

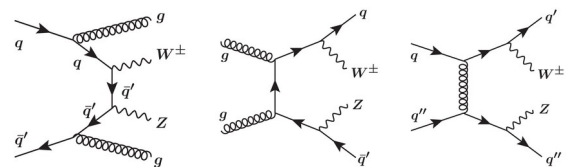


Sherpa3 0,1j LO polarised

Sherpa2.2.12/14 0,1j LO inclusive

Main background : WZjj-QCD

67% of SR events



Sherpa2.2.12/16 NLO QCD +
0,1,2,3j (Comix & OpenLoops)

Interference:

0.8% of
SR events

Other backgrounds

- Fake leptons (6%)
→ Matrix Method (data driven)
- ZZjj EW + QCD (6%)
→ ZZ CR
- tZj (3.5%) + ttV (2.3%)
→ b-CR
- WZjj in τ , Tribosons (<1%)

$W_0 Z_0$: ~1% of SR events

$W_0 Z_T$: ~2.5% of SR events

$W_T Z_0$: ~2.5% of SR events

$W_T Z_T$: ~7.2% of SR events

Challenge : low signal events yields

~650 (Run2) + ~950 (partial Run3) events

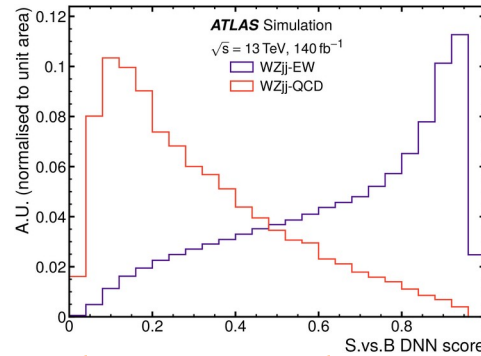
→ ~200 WZjj-EW signal events

Signal vs Background separation

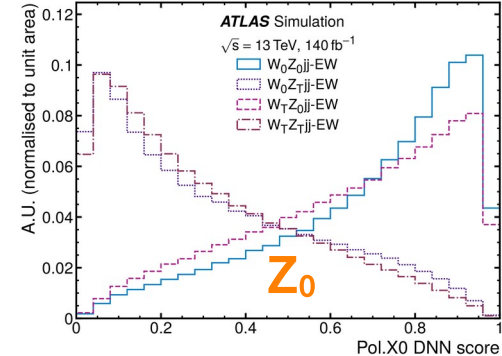
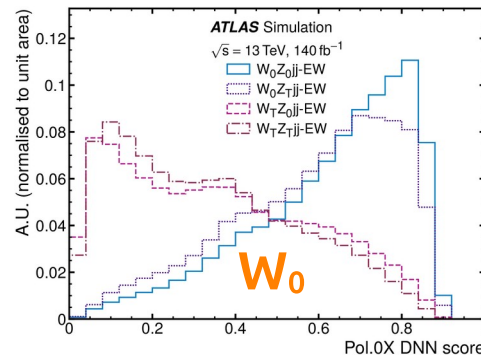
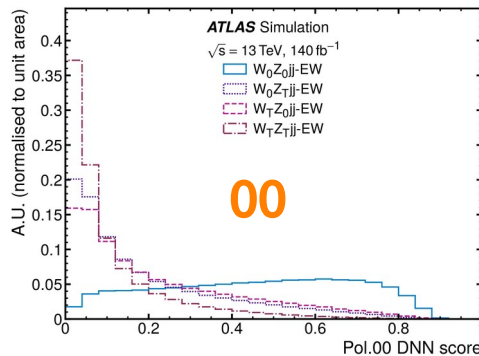
3 fits, 1 template against 3 others : **00** vs others ($0T + T0 + TT$) ; **W_0** vs W_T ; **Z_0** vs Z_T

2 types of DNN

– **WZjj-EW** vs other **SM backgrounds** (18 variables)



– **Target WZ polarisation** vs **other WZ polarisations** (using subsets of 29 variables)



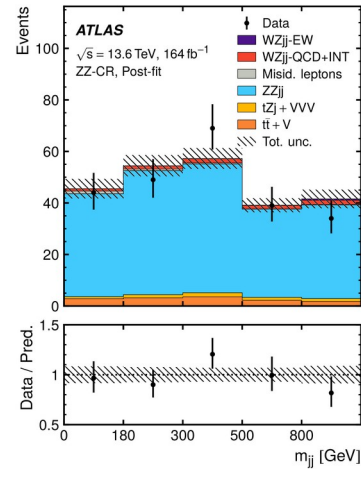
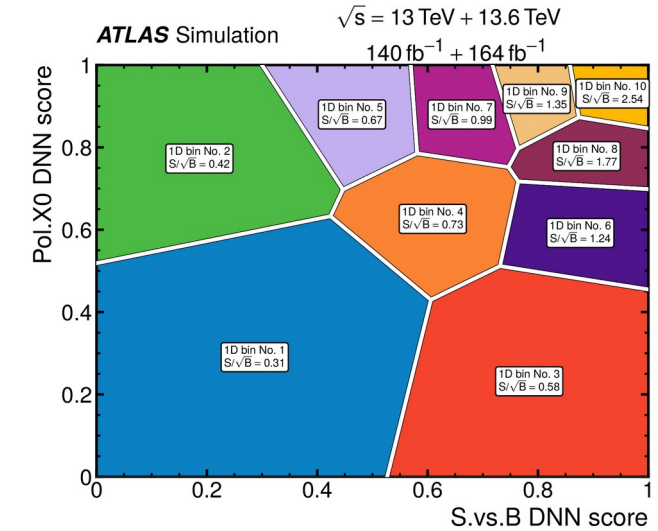
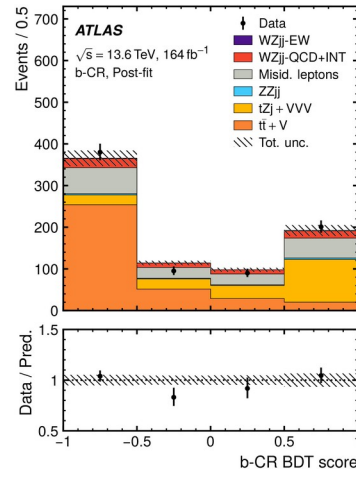
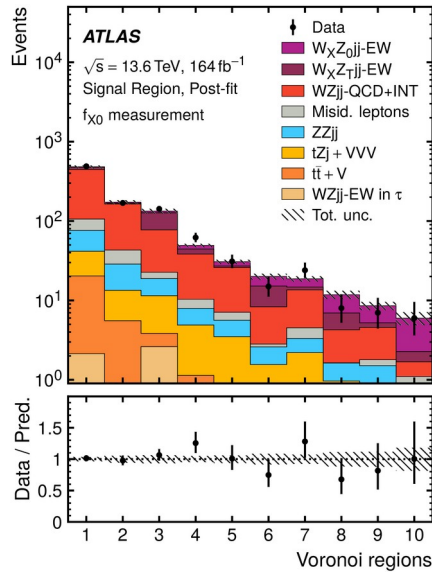
Fit setup

Combine DNN in Voronoï regions along $S/\sqrt{B}$

→ **3 Discriminating variable** for **3** template fits

Fit simultaneously with

- ZZ-CR and b-CR
- Run 2 and Run 3 data



Templates Modelling

Nominal **polarisation** templates : **Sherpa3 0,1j LO polarised** (~real NLO QCD corrections)

- Shape uncertainty with **alternative sample Madgraph LO polarised**

- $\leq 20\%$ uncertainty (*mainly low $S/\sqrt{B}$ regions*)

- Shape uncertainty on **Voronoi regions** with **fixed order calculation**
by **MoCaNLO NLO EW polarised** (*provided parton/particle and particle/detector level reweightings*)

- $\leq 20\%$ uncertainty for the 4 polarisation templates

WZjj-QCD modelling : **Sherpa2.2.12/16 NLO QCD + 0,1,2,3j (Comix & OpenLoops)**

- Standard **7 point variation for QCD** uncertainty yields very big uncertainties ($\leq 40\%$)

- Validated in inclusive WZ VBS

- Shape uncertainty with **alternative sample Madgraph NLO QCD + 0,1,2j**

- $\leq 30\%$ uncertainty (*mainly high $S/\sqrt{B}$ regions*)

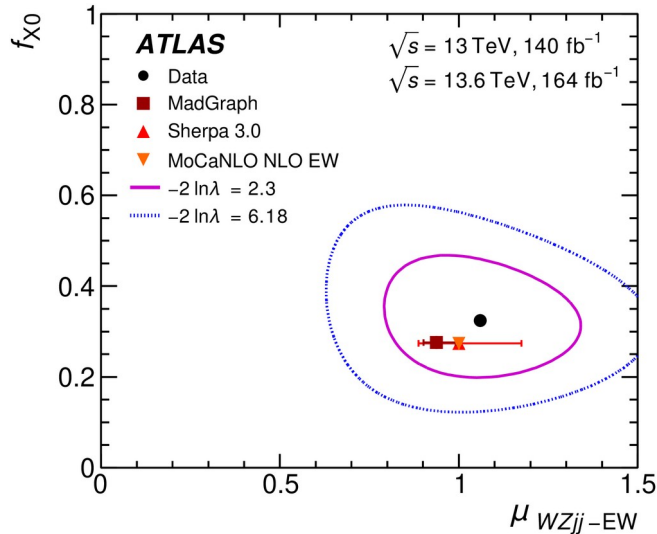
Result : Evidence for Z_0 polarisation

5 parameter fit : **agreement with SM**

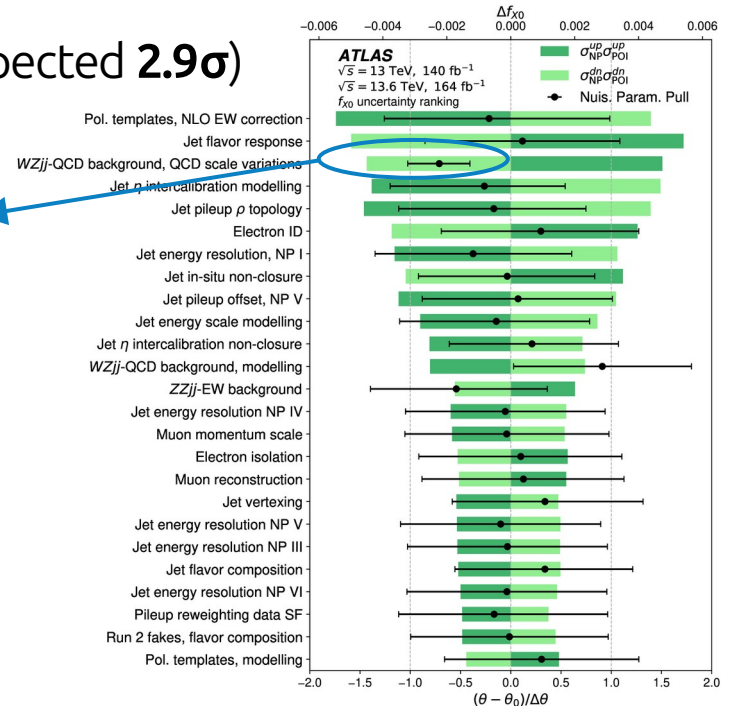
- Control regions $\mu_{ttV} = 0.96 \pm 0.12$ (1.09 ± 0.14), $\mu_{tZj} = 1.18 \pm 0.22$ (1.15 ± 0.22) and $\mu_{ZZ} = 1.09 \pm 0.11$ (0.97 ± 0.11)
- Signal inclusive Wzjj-EW normalisation $\mu_{WZjj-EW}$: agreement with SM → **cross section for Run3**

$$\sigma_{WZjj-EW}^{13.6 \text{ TeV}} = 0.374 \pm 0.077 \text{ (stat.)} \pm 0.053 \text{ (syst.)} \pm 0.009 \text{ (lumi.) fb}$$

- Z boson polarisation fraction f_{X0} : evidence at **4.0 σ** (expected **2.9 σ**)



*WZjj-QCD scale variation
scaled down to 0.74
→ consistent with ~40%
uncertainty
→ consistent with WZjj
inclusive measurement*



Uncertainties

Main uncertainties

- **Statistically dominated**
- **Modelling**
- **Jets**
(~NLO QCD real corrections)

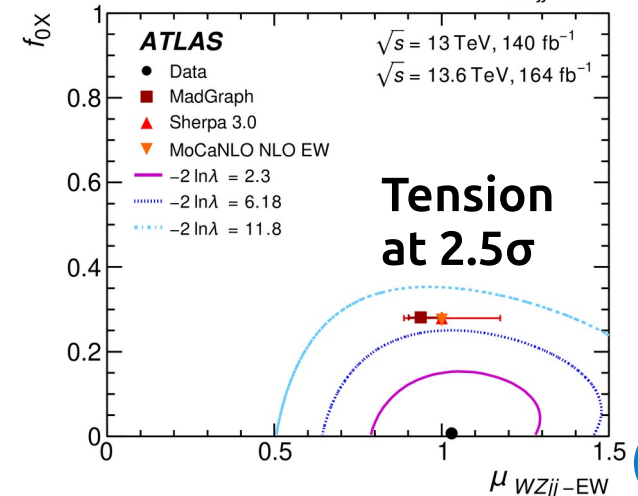
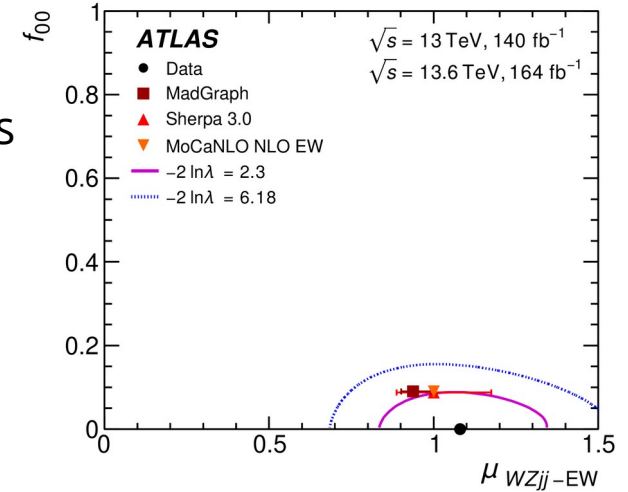
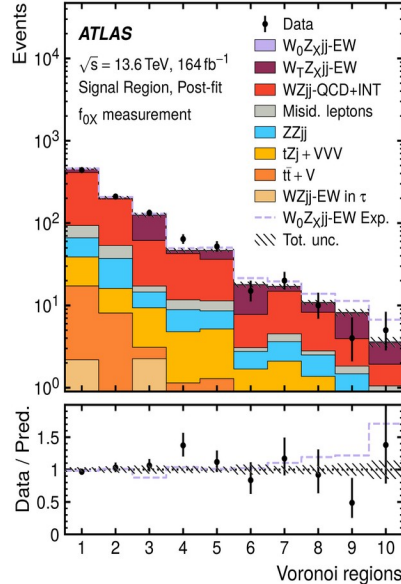
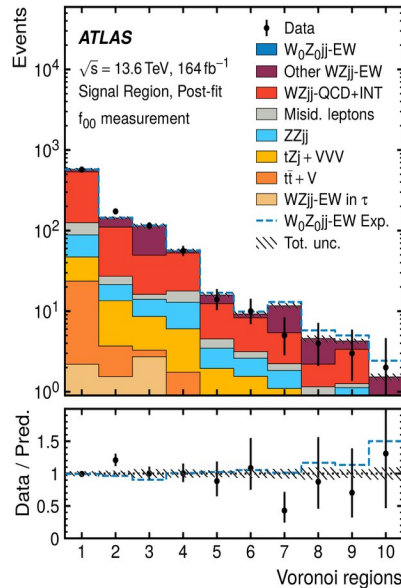
	f_{X0}	$\mu_{WZjj-EW}$
Relative uncertainty [%]		
$WZjj$ –EW Theory modelling	1.7	4.9
$WZjj$ –QCD Theory modelling	1.6	5.0
$WZjj$ –INT Theory modelling	<0.1	0.4
PDFs	0.3	0.7
Electrons	1.3	1.6
b -tagging	0.5	0.5
Jets	3.6	6.6
E_T^{miss}	0.3	0.5
Muons	0.8	0.9
Pile-up	0.5	1.9
Other backgrounds	0.8	1.3
Misid. leptons background	0.6	1.0
MC statistics	2.4	1.1
All systematics	5.3	10.2
Luminosity	0.4	1.2
Statistics	26.6	13.8
Total	27.1	17.2

Limits on f_{00} and f_{0X}

No significant number of events post-fit for W_0Z_0 or W_0Z_X
 ➔ Expected 1.3σ (W_0Z_0) and 2.6σ (W_0Z_X) against null hypothesis

95% CL upper limits :

	Fraction	Expected	Observed
f_{00}		0.21	0.12
f_{0X}		0.46	0.19



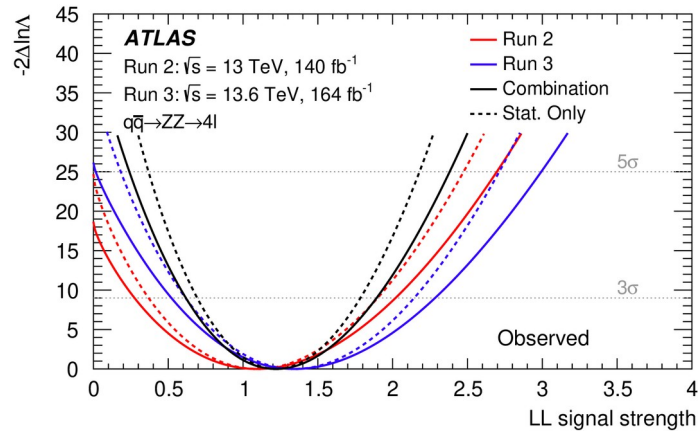
CONCLUSION

CONCLUSION

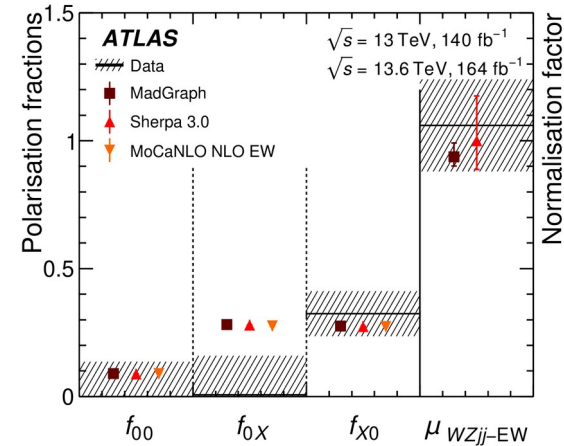
Polarisation being measured across diboson signatures

- Precision measurement in **inclusive diboson**
- Becoming accessible in **Vector Boson Scattering**

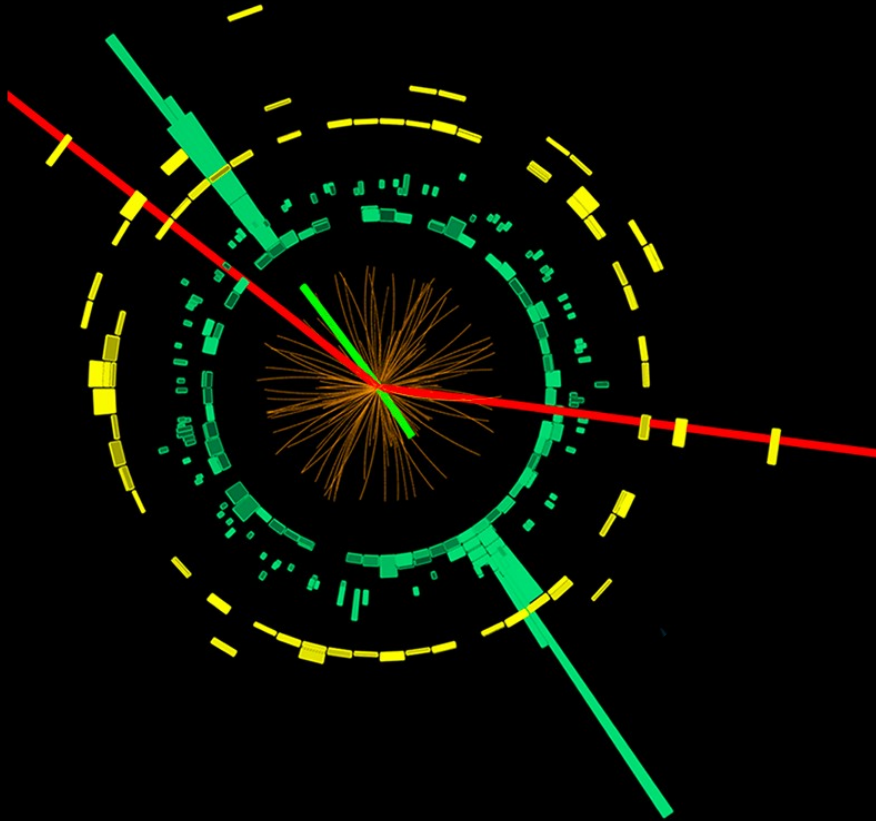
Limited by **statistics** and theoretical **modelling**



*Observation of f_{00} in
inclusive ZZ*



*First attempt at joint-polarisation
measurement in **WZ VBS***



*Thank you for
your attention*

Run: 456714

Event: 1835283836

2023-07-15 23:57:23 CEST

ZZ event display

Results at LEP

Only **diboson process** accessible for such measurements: $e^+ e^- \rightarrow W^+ W^-$

Single W boson polarisation measurements:

→ L3 [arXiv:0301027], OPAL [arXiv:0312047], DELPHI [arXiv:0801.1235]

Joint-polarisation measurements:

→ L3 [arXiv:0501036]: **only correlations** between bosons polarisation (decay planes)

→ DELPHI [arXiv:0908.1023]: **not sensitive** enough to f_{00}

→ OPAL [arXiv:0009021]: **almost 3σ** for f_{00} , but **tension** with Standard Model

$$\bar{\rho}_{TT} = (67 \pm 8)\%,$$

$$\bar{\rho}_{LT} = (30 \pm 8)\%,$$

$$\bar{\rho}_{LL} = (3 \pm 7)\%.$$

DELPHI results

	Measured	Expected
$\sigma_{TT}/\sigma_{\text{total}}$	$0.781 \pm 0.090 \pm 0.033$	0.572 ± 0.010
$\sigma_{LL}/\sigma_{\text{total}}$	$0.201 \pm 0.072 \pm 0.018$	0.086 ± 0.008
$\sigma_{TL}/\sigma_{\text{total}}$	$0.018 \pm 0.147 \pm 0.038$	0.342 ± 0.016

OPAL results

ZZ event selection

4 isolated leptons with invariant masses compatible with 2 Z bosons

Leptons	
Muons	$p_T > 5 \text{ GeV}, \eta < 2.5$
Electrons	$E_T > 7 \text{ GeV}, \eta < 2.47$
Lepton selection and quadruplet formation	
Lepton kinematics	$p_T > 27/20 \text{ GeV}$ for the leading and sub-leading leptons
Lepton separation	$\Delta R_{ij} > 0.05$ for any two leptons
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5 \text{ GeV}$ for all Same-Flavor, Opposite-Charge (SFOC) pairs
Quadruplet formation	Quadruplet with the smallest $ m_{Z_1} - m_Z + m_{Z_2} - m_Z $
On-shell requirements	
On-shell Z boson	$ m_{ij} - m_Z < 10 \text{ GeV}$
On-shell ZZ pair	$m_{4l} > 180 \text{ GeV}$
Signal region definition	
Signal region	The selected quadruplet contains 4 <i>signal</i> leptons
Low-mass signal region	$180 < m_{4l} < 240 \text{ GeV}$
High-mass signal region	$m_{4l} \geq 240 \text{ GeV}$

Differences with previous Run2 ZZ paper

	Original Run 2	Updated Run 2
Changes of the polarization modeling		
$gg \rightarrow ZZ$ treatment	Signal	Background
Interference modeling	Prediction from MoCANLO	Prediction from SHERPA 3
$q\bar{q} \rightarrow ZZ$ modeling uncertainties	NLO reweighting observable choice and residual non-closure	SHERPA 3 shape difference
Change of results		
Expected LL signal strength	1.00 ± 0.27	1.00 ± 0.27
Observed LL signal strength	1.15 ± 0.29	1.09 ± 0.29
Expected LL significance	3.8	4.2
Observed LL significance	4.3	4.3

WZ VBS event selection

3 leptons, 2 jets, missing E_T

Variable	$WZjj$ –EW signal region
ZZ veto	Less than 4 “loose” leptons
N leptons	Exactly three leptons passing the “medium” lepton selection
Leading lepton p_T	$p_T^{\text{lead}} > 27$ GeV (25 GeV in 2015)
Z leptons	Two same flavour oppositely charged leptons passing the “medium” lepton selection
Mass window	$ M_{\ell\ell} - M_Z < 10$ GeV
W lepton	Remaining lepton passes the “tight” lepton selection
W transverse mass	$m_T^W > 30$ GeV
p_T two leading jets	> 40 GeV
$ \eta_j $ two leading jets	< 4.5
Jet multiplicity	≥ 2
$\eta_{j1} \cdot \eta_{j2}$	< 0
m_{jj}	> 500 GeV
$N_{b\text{-quark}}$	$= 0$

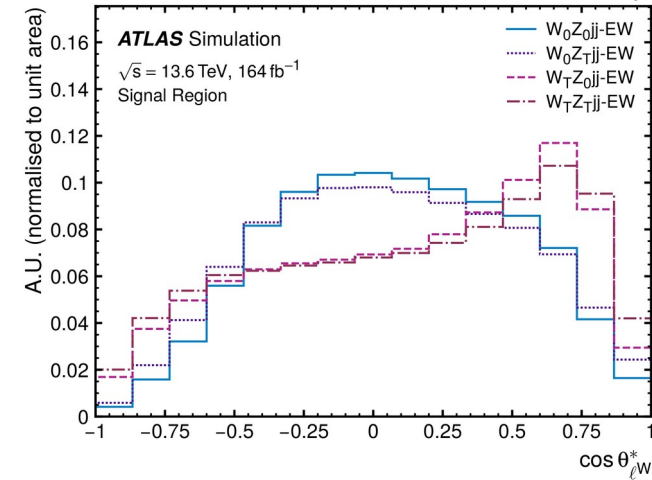
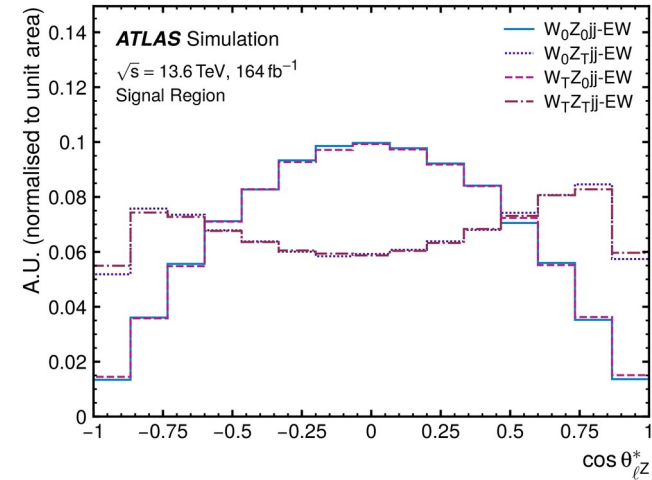
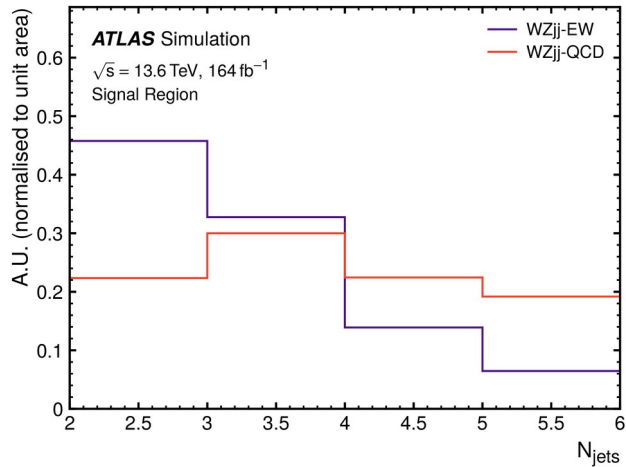
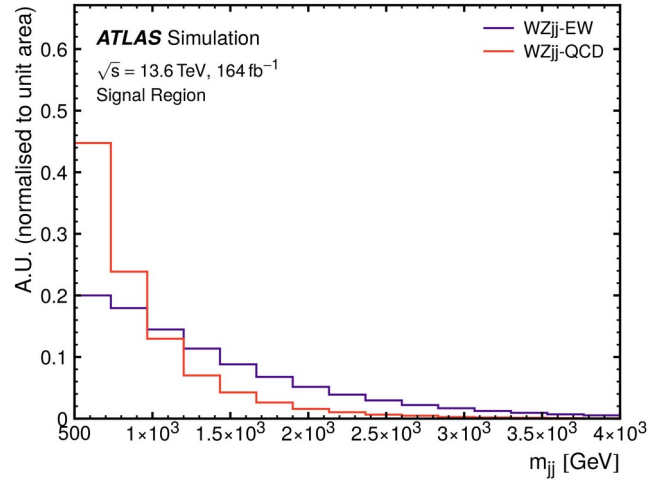
Fiducial phase space

Variable	Fiducial inclusive
Lepton $ \eta $	< 2.5
p_T of ℓ_Z , p_T of ℓ_W [GeV]	$> 15, > 20$
m_Z range [GeV]	$ m_Z - m_Z^{\text{PDG}} < 10$
m_T^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	$> 0.2, > 0.3$
p_T two leading jets [GeV]	> 40
$ \eta_j $ two leading jets	< 4.5
Jet multiplicity	≥ 2
$\eta_{j1} \cdot \eta_{j2}$	< 0
m_{jj} [GeV]	> 500
$\Delta R(j, \ell)$	> 0.3

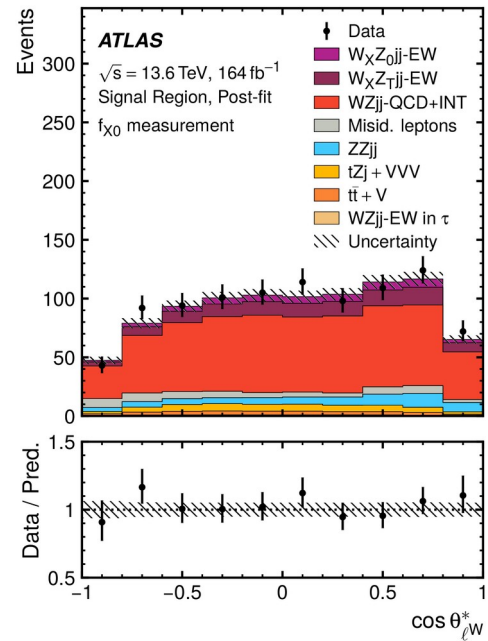
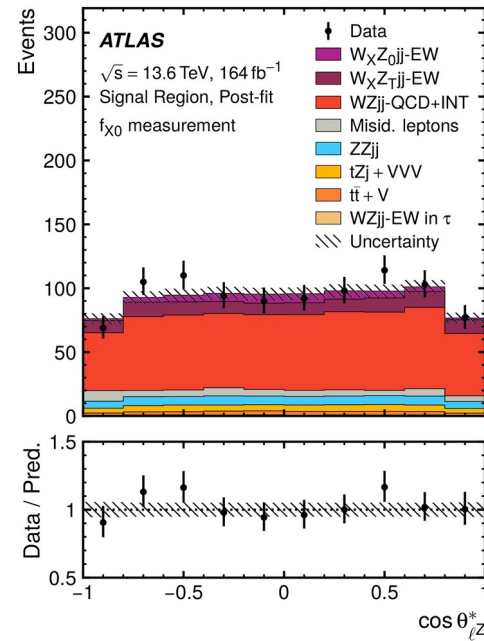
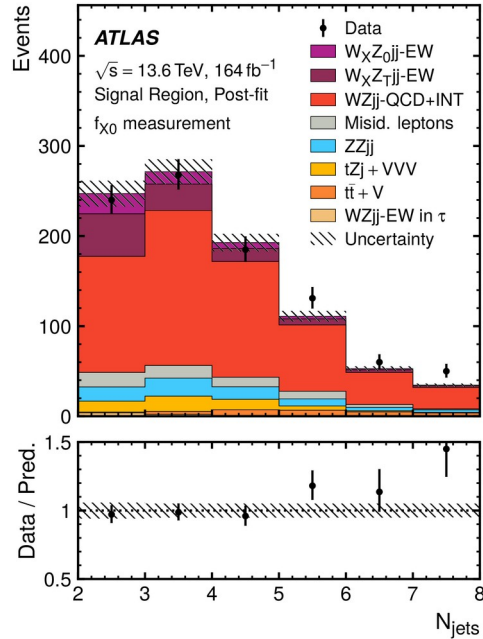
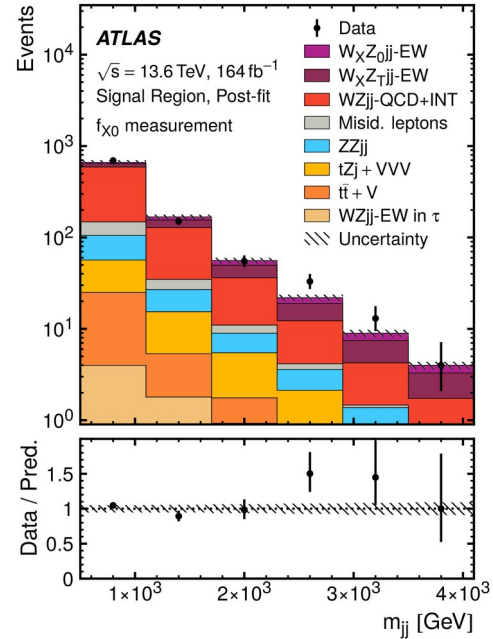
WZ DNNs variables

Symbol	Description	S.vs.B	Pol.00	Pol.0X	Pol.X0
<i>Event topology</i>					
$\zeta_{\text{lep.}}$	Centrality of the WZ system relative to the tagging jets	✓			
$ y_Z - y_{\ell,W} $	Rapidity difference between Z boson and lepton from W decay	✓	✓	✓	✓
z_ℓ	Zeppenfeld variable [77] for leptons				✓
N_{jets}	Multiplicity of jets with $p_T > 25$ GeV	✓			
$R_{p_T}^{\text{hard}}$	Ratio of vectorial to scalar p_T sum of jets	✓			
<i>Tagging jets</i>					
$p_T^{j_1}$	Transverse momentum of leading tagging jet	✓			✓
$p_T^{j_2}$	Transverse momentum of sub-leading tagging jet				✓
η^{j_1}	Pseudorapidity of leading tagging jet		✓	✓	✓
η^{j_2}	Pseudorapidity of sub-leading tagging jet	✓	✓	✓	
ϕ^{j_2}	Azimuthal angle of sub-leading tagging jet			✓	
E^{j_1}	Energy of leading tagging jet	✓			
m_{jj}	Invariant mass of the dijet system	✓			
$\Delta\eta_{jj}$	Pseudorapidity difference between the two tagging jets	✓	✓	✓	✓
$\Delta\phi_{jj}$	Azimuthal angle difference between the two tagging jets	✓	✓	✓	
$\Delta R(j_1, Z)$	Angular separation between the leading jet and the Z boson		✓	✓	✓
$\langle p_T^T \rangle$	Average transverse momentum of the two tagging jets				✓
$A_{p_T^{ij}}$	Asymmetry in p_T between the two tagging jets	✓	✓	✓	
<i>Boson kinematics</i>					
p_T^W	Transverse momentum of the W boson	✓	✓	✓	✓
p_T^Z	Transverse momentum of the Z boson		✓	✓	✓
p_T^{WZ}	Transverse momentum of the WZ system	✓	✓	✓	✓
m_T^{WZ}	Transverse mass of the WZ system		✓	✓	✓
r_{21}	Ratio of leading to sub-leading boson p_T		✓		
<i>Lepton kinematics</i>					
$p_T^{\ell_1^Z}$	Transverse momentum of leading Z lepton		✓		✓
$p_T^{\ell_2^Z}$	Transverse momentum of second Z lepton				✓
$p_T^{\ell^W}$	Transverse momentum of W lepton			✓	✓
$\eta^{\ell_1^Z}$	Pseudorapidity of leading Z lepton	✓	✓	✓	✓
$\eta^{\ell_2^Z}$	Pseudorapidity of second Z lepton		✓		✓
η^{ℓ^W}	Pseudorapidity of W lepton	✓	✓	✓	✓
E_T^{miss}	Missing transverse momentum			✓	✓
<i>Angular and polarisation-sensitive observables</i>					
$\cos\theta_{W^*}^*$	Cosine of decay angle in the W rest frame relative to the WZ rest frame		✓	✓	
$\cos\theta_{Z^*}^*$	Cosine of decay angle in the Z rest frame relative to the WZ rest frame		✓		✓
$ \cos\theta_V $	Cosine of decay angle in the WZ rest frame	✓	✓	✓	
$\Delta\phi(\ell_1^Z, \ell_2^Z)$	Azimuthal angle difference between leptons from the Z	✓	✓		
$\Delta\phi(\ell^W, \nu)$	Azimuthal angle difference between lepton and neutrino from the W	✓		✓	

WZ DNNs input variables distributions



WZ DNN modelling check



WZ VBS fit result

	Data $\pm$ total ($\pm$ stat., $\pm$ syst., $\pm$ lumi.)	MADGRAPH	SHERPA 3.0	MoCANLO NLO EW
f_{00}	0.000 ± 0.134 (± 0.134 , ± 0.000 , ± 0.000)	0.0902 ± 0.0005	0.087 ± 0.001	0.0902 ± 0.0005
f_{0X}	0.007 ± 0.151 (± 0.150 , ± 0.018 , ± 0.001)	0.2808 ± 0.0002	0.2793 ± 0.0009	0.2758 ± 0.0008
f_{X0}	0.324 ± 0.088 (± 0.086 , ± 0.017 , ± 0.001)	0.2758 ± 0.0003	0.274 ± 0.001	0.2745 ± 0.0008
$\mu_{WZjj-EW}$	1.06 ± 0.18 (± 0.15 , ± 0.11 , ± 0.01)	$0.94^{+0.05}_{-0.04}$	$1.00^{+0.2}_{-0.1}$	—

	Combined	Individual fits	
		Run 2	Run 3
	$\pm$ total ($\pm$ stat., $\pm$ syst., $\pm$ lumi.)		
f_{00}	0.000 ± 0.134 (± 0.134 , ± 0.000 , ± 0.000)	0.056 ± 0.091 (± 0.090 , ± 0.009 , ± 0.000)	0.000 ± 0.051 (± 0.051 , ± 0.000 , ± 0.000)
f_{0X}	0.007 ± 0.151 (± 0.150 , ± 0.018 , ± 0.001)	0.000 ± 0.207 (± 0.207 , ± 0.000 , ± 0.000)	0.024 ± 0.130 (± 0.128 , ± 0.022 , ± 0.001)
f_{X0}	0.324 ± 0.088 (± 0.086 , ± 0.017 , ± 0.001)	0.411 ± 0.136 (± 0.134 , ± 0.024 , ± 0.000)	0.270 ± 0.127 (± 0.124 , ± 0.028 , ± 0.001)
$\mu_{WZjj-EW}$	1.055 ± 0.181 (± 0.146 , ± 0.108 , ± 0.013)	1.037 ± 0.236 (± 0.204 , ± 0.118 , ± 0.010)	1.004 ± 0.252 (± 0.206 , ± 0.145 , ± 0.024)
$\sigma_{WZjj-EW}^{13\text{ TeV}}$	0.353 ± 0.061 (± 0.049 , ± 0.036 , ± 0.004)	0.347 ± 0.079 (± 0.068 , ± 0.039 , ± 0.003)	—
$\sigma_{WZjj-EW}^{13.6\text{ TeV}}$	0.393 ± 0.068 (± 0.054 , ± 0.040 , ± 0.005)	—	0.374 ± 0.094 (± 0.077 , ± 0.054 , ± 0.009)

	Fraction	Expected	$\pm 1\sigma$	$\pm 2\sigma$	$\pm 3\sigma$	Observed
f_{00}		0.21	[0.15, 0.29]	[0.08, 0.36]	[0.02, 0.44]	0.12
f_{0X}		0.46	[0.35, 0.58]	[0.24, 0.70]	[0.13, 0.81]	0.19